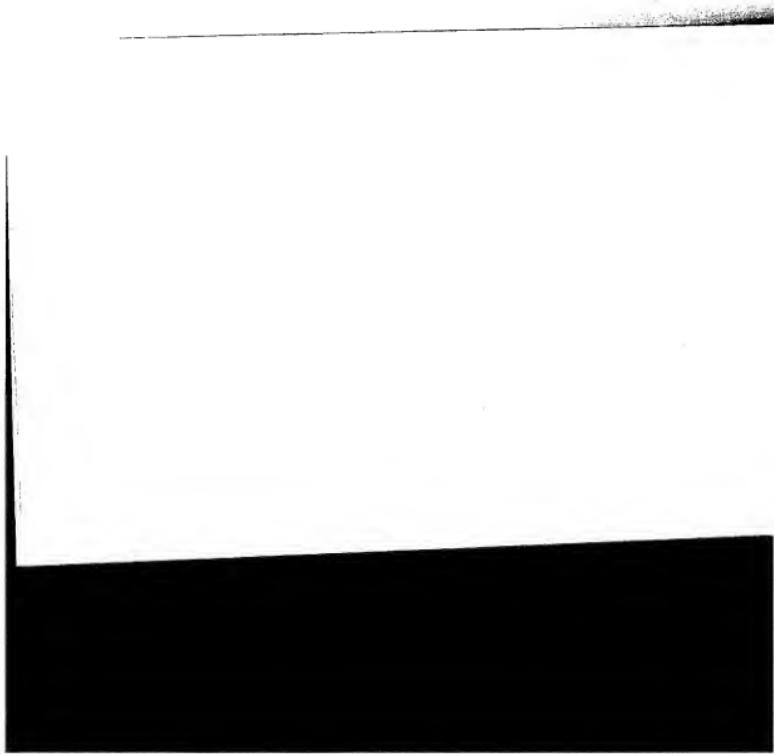


Solution Mining



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To
Mr. and Mrs.
for teaching extractive
and mineral engineering
and pointing

for teaching extractive metallurgy science and mineral engineering practice, and pointing the way

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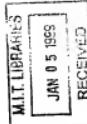
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PREFACE

This text is derived from a course in solution mining taught to metallurgical and mining engineers at the University of Idaho. The course was aimed to provide an introduction to the rapidly expanding field of solution mining, particularly for the extraction of gold, silver, and copper. The annual economic value of solution mined metals in the United States now exceeds that of metals extracted by underground mining. But solution mining is a relatively new field, at least at its present scale. It has not been part of the established academic curricula and has been taught only as an elective subject at a few institutions and in short courses given by companies. Although several solution mining symposium proceedings have been published in recent years, primarily by the Society of Mining, Metallurgy and Exploration, an integrated text with problems suitable for undergraduate, practicing engineers and geologists was not available. Keeping in mind this broad audience spectrum, this book has been designed to require only a preliminary understanding of basic inorganic chemistry. Although mathematical modeling has made contributions to understanding solution mining phenomena, it is eschewed somewhat in the interest of a wider audience of practitioners, except for chapter 12.

I first became interested in solution mining in 1971 after spending a summer at Lawrence Livermore Laboratory (L.L.L.) where a huge pilot plant scale pressurized leaching experiment was underway to experimentally simulate copper extraction by flooded leaching at depth. Livermore was then pursuing peaceful uses of nuclear explosives, and investigating *in situ* mobilization of ore using nuclear explosives prior to leaching. Experimental results were explained by a computer simulation model published in 1972. Before that I had been stimulated by Prof. Milton Wadsworth, while a student at the University of Utah.

During summers of the early 1970s, I solution mined gold contained in low grade ore heaps left from a previously operated Nevada gold mine. Since then, leach leaching gold ore has become a billion-dollar industry in Nevada.

From 1973 to 1978, as manager of hydrometallurgy at the Kemetco Research Center in Salt Lake City, I participated in major laboratory and mine site experiments to better understand copper leaching from mine waste dumps. This major source of domestic copper production involves many interrelated complex phenomena, and the Kemetco research during this period (subsequently extensive) was the most extensive yet conducted on this important aspect of metal mining.

On testing of precious metal deposits returned to the fore during the 1980s, along with studying the solution mining of borates, while I was directing the Arizona Materials' Tucson Research Center. Recently, I have been interested in bioremediative pretreatment of low-grade refractory gold ores in bacteria inoculated wet stockpiles, prior to cyanide heap leaching.

I am indebted to many colleagues over a span of more than twenty years for the experiences, ideas and friendships shared during our mutual interest in solution mining. Principals among these are Jay Agarwal, John Apps, Rehan Bhatta, Rob Brann, Al Brysonston, Larry Cahills, Don Davidson, Jerry Fountain, Joe Harrington, Rudy Jacobson, Jonathan Jackson, Bill Larson, Art Lewis, Ed Malone, Dave Milligan, Keith Prichbey, Bruce Ream, Dave Reese, Ken Richards, Ron Roman, Joe Schiltz, John Shert, Rush Spedden, Dick Van Zyl, Milton Wadsworth and Roll Wiesley.

I am especially grateful to Joe Schiltz, Milt Wadsworth and the late Don Davidson for critical reviews of the first-edition manuscript and many useful suggestions. Rudy Jacobson, Milt Wadsworth and David Dixon were helpful with this new edition.

Text and illustration preparation and editing were accomplished with

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and Pat Hanrahan, for which I am most grateful.

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Introduction

SCOPE OF SOLUTION MINING

Solution mining is variously defined. In this text it includes all forms of extraction of materials from the earth by leaching and fluid recovery, both by site methods and heap leaching of excavated ore. The emphasis is on minerals, berries and other naturally occurring solutions, but the theory and practice developed for these materials can be extended to contaminants introduced into the earth by human activity. Several minerals are readily soluble in water, forming brines, and recovery of these fluids resonates the earliest applications of solution mining. Extraction of solid minerals by an aqueous solution flowing through and leaching (dissolving) them from their host rock has become of increasing importance in solution mining. This includes both readily soluble evaporite minerals and minerals requiring leaching, reactions with acids or other chemical incants and, often, oxidation of the material. In outlining the scope of solution mining in this introductory chapter, some words will be contextually defined as they are conventionally used in solution mining practice.

Solution mining is an interdisciplinary field involving geology, chemistry, hydrology, extractive metallurgy, mining engineering, process engineering and economics. A few of the features to be considered in solution mining projects are: leaching chemistry; rock (gangue) chemistry; solution flow in the ore mass; air flow in the ore mass (percolation leaching); open void space in the ore mass available for flow; ore (rock) microstructure; transport within dead end micro pores by ordinary chemical diffusion, metal/mineral recovery technology and operations and their effect on

leaching extraction, environmental containment, solution losses, brine chemistry, and natural evaporation pond engineering and reclamation.

The approach of this text is to include description, theory and practical aspects of current solution mining technology. Principles will be integrated with specific metal/mineral systems and practice, beginning with simple systems and proceeding toward increasing complexity. Understanding the important factors, their relationship with each other and their influence on the technological and economic outcome are not sufficient to detail. Mathematical modeling of solution mining systems should aim at providing improved understanding of these complex phenomena rather than a numerical centroid.

At the present time water is the only solvent base of commercial interest, with the exception of molten sulfur recovered using hot water in the Frasch process, so this text's discussion will be focused on aqueous systems. Generally the principles are transferable. *In situ* or "true" solution mining involves extraction of minerals from the unindurated ore in place. Leaching of ore established within the ore body is sometimes referred to as "in-situ" solution mining. Extraction of the ore using conventional mining methods followed by heap leaching in prepared ore stockpiles on the surface and dump leaching of mine overburden (waste) are important applications of solution mining that will be covered in this text. The extraction operation (leaching, brine recovery, etc.) is coupled with a metal/mineral separation operation, nearly always on the surface and adjacent to the extraction operation for separation of the dissolved metals or minerals from the recovered fluid or leachate. Large volumes of solution circulate between the extraction and separation operations. Both gravity flow and pumping are used to transport the leaching fluids. Leachates generated by the extraction operation are often referred to as "pregnant solutions" or pregnant liquids, while fluids being returned to the extraction operation are often referred to as "barren solutions" for obvious reasons. Sometimes solution is bled from the otherwise closed circulating solution to control the accumulation of undesirable impurities. This text will focus on extraction operations and will either omit or only peripherally include mineral and metal recovery from solutions. The science and engineering of metal separation technologies are described in hydrochemical texts including Habashi (1980) and Van Arsdel (1965).

Sufficient permeability in the ore mass to permit solution flow is

open to provide good permeability. Evaporites contain large amounts of soluble mineral and therefore tend to become more open as extraction proceeds.

Many metallic minerals were deposited by geochemical processes that involved hydrothermal solutions flowing in natural rock fractures. If these fractures remain open, they can be a source for extraction by solution mining. However, host rocks for sulfide ore deposits typically contain fractures with a micro porosity of only about 1–6% and very low permeabilities—often too low for commercial production rates in solution mining. Also, major fractures are a source of high flow channels that short-circuit the solution, not allowing it to sweep uniformly through most of the ore mass. This leads to low sweep efficiency, low yield of extracted metal/mineral, and often economic failure. Furthermore, the uncertainty in sweep efficiency causes uncertainty in economic forecasting, which prevents many solution mining projects from being implemented. Not only adequate permeability but fairly uniform permeability is required.

Success often requires substantial increase in permeability by fragmenting the ore in place, nibbling. Effective fragmentation readily allows a substantial increase in volume, 15–20%, to provide open space for flow channels. Planned deliberate caving, blasting and open subsidence over underground excavations and abandoned mines are ready sources; the overlying subsidence provides a large volume of broken ore. Leaching caved fragments over otherwise depleted underground mines is a common application of solution mining.

Both Headed Leaching and Percolation Leaching, or trickle leaching, are employed in solution mining. Flooded leaching pertains to situations where the ore mass is saturated with the solution; usually only one fluid phase is present and the operation typically occurs below the water table, or the solution is otherwise contained. Flooded leaching has many flow characteristics in common with ground water flow. The mathematical treatment and numerical models describing flow problems in hydrology are often readily transferable. Percolation leaching involves downward flow of unsaturated solution by gravity; two fluid phases, solution and air, are always present within the ore mass. Other distinguishing characteristics of percolation leaching and flooded leaching are presented in Table 1.1. Many aspects of solution mining are treated in the Mining Engineering Handbook (2nd edition, 1992).

Environmental contamination of solution must always be minimized in a solution mining operation, and various approaches to achieve this will be discussed in the text. Remediation of contaminated ground and water, including groundwater, is covered in the fast chapter.

Table 1.1 Characteristics of Percolation and Flooded Leaching.

PERCOLATION LEACHING

— Solution trickles downward by gravity in an adequately permeable ore mass.

— Solution must be uniformly spread over the top of the ore mass and collected at the bottom of the ore mass, over an impervious bottom layer to prevent further downward percolation.

— Adequate permeability is usually achieved by fragmentation from mining and/or additional ore crushing. Excessively fine or clay-like ore with low permeability may be agglomerated to improve permeability.

— The solution is not saturated and air is present, which may or may not be important to the leaching chemistry. If oxygen is consumed the air may be partially oxygen-depleted.

— Leaching applications are leach leaching, grind, leach, copper, and uranium, copper mine waste dump leaching, leaching mine tailings for copper and uranium.

FLOODED LEACHING

— Solution flows because of a pressure gradient, often from an injection well(s) to a production well(s), through an adequately permeable ore mass.

— Air is not normally present, although injection of air or oxygen at a chemical resistant bubbling upward through the otherwise solution saturated ore mass may occur; this is an example of two-phase flow.

— Leaching occurs only below a water table, either natural or artificially induced.

— The permeability must be nearly uniform to provide good sweep efficiency and extraction; the ore zone must be bound by ground of substantially lower permeability to prevent solution flow into a region of relatively permeable ore.

— Leaching applications are brine or production flame wells, leaching uranium and copper (ground limited to a depth of 100 m), leaching uranium below the water table.

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copper and uranium are soluble in acidic solutions at a sufficiently low pH—below their hydroxyl pH. Sulfuric acid is commonly used, primarily because of its low cost. Oxidized uranium is also soluble in ammonium carbonate solutions, and this lixiviant is used when the uranium ore contains limestone, dolomite or other major acid-consuming gangue minerals.

Chemical oxidation of the economic minerals, or other minerals in the ore, is often required to render them soluble. Hydrogen peroxide is often used for this purpose in uranium leaching. Although oxygen is required to solubilize gold in cyanide leaching, the amount is small. For most heap leaching applications where ore is free of sulfides and organic material, oxygen dissolved in the leach solution is adequate. Leaching sulfide or carbonaceous ores is another matter. Large amounts of oxygen are required to oxidize sulfide minerals and for many ores and mine wastes air is the only affordable source of oxygen. Furthermore, the solubility of oxygen dissolved in aqueous solutions is insufficient for commercial production rates. Hence, these leaching systems must have both the solution phase and the air phase present and flowing through the ore mass being treated, a case of two-phases flow.

Because of oxygen's low solubility near room temperature, leaching of sulfides and other minerals requiring oxidation would be very slow except for the presence of ferric ions. Fortunately, iron is a ubiquitous element in the earth and most nonferrous ore mineral assemblages. Ferric ions are often present in the ore leaching solution as the primary oxidant. However, the regeneration of ferric ions (from the ferrous ions resulting from mineral oxidation) is kinetically very slow without the assistance of *liberators* (pyrograders). These bacteria catalyze the oxidation of both ferrous ions and sulfide minerals. Thus, biooxidation of minerals is an important aspect of many solution mining applications. The role of bacteria and bacteria products such as enzymes has expanded into many aspects of solution mining, including environmental treatment of spent solutions, waste water, and hazardous residues as well as mineral oxidation. Biohydrometallurgy has recently evolved as a new field of research and industrial practice, which has been exhaustively reviewed in a text by Rossi (1996) that includes over 1,600 references.

IMPORTANCE OF SOLUTION MINING

When technically feasible, the specific treatment cases of solution mining can often be substantially lower than any other approach. Consequently, as lower grade ores are being mined, solution mining is often the only available

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Table 1.2 Importance of Solution Mining for USA Selected Metal/Minerals.

Metal or Mineral	Approximate Primary Production
Gold	35%
Silver	25%
Copper	30%
Uranium	75%
Common Salt	50%
Potash	20%
Iron	20%
Barium	85%
Magnesium	85%
Sulfur	35%

route and its use is rapidly expanding. Solution mining ore in heaps and leaching mine waste dumps are well matched to excavation (mining) of bulk ore deposits using large-scale surface mining equipment, which has evolved during the last few decades to provide remarkably low specific mining costs, sometimes less than one US dollar per tonne of ore (1 tonne = 1 metric ton = 1 Mg).

The author's estimates of the percentage of the primary production attributed to solution mining in the United States are shown in Table 1.2. These estimates are part based on the US Bureau of Mines Mineral Commodity Summaries. In 1990, the added value of solution mining operations in the western United States was approaching two billion dollars. This figure does not include the value or equivalent cost of associated conventional mining operations to provide ore for leaching in heaps and mine dumps, nor the value of subsequent metals separation operations such as solvent extraction, electrolysmelting and metal refining. The magnitude of solution mining in the western United States is now easily greater than that of underground hard rock mining of non-fuel minerals, and it is expanding rapidly. Many low grade gold mines, opened in the last decade and operating profitably, would not be possible without the low cost leaching of ore in heaps.

SHARPENING OUR INTUITIVE UNDERSTANDING OF LEARNING

Let us begin with a simple leaching system and a few experiments the results of which we can easily comprehend, and even perform without

benefit of a laboratory. This might be called "the kitchen series." Consider an event that we are all familiar with—an dissolution of sugar in a cup of coffee, or to more observable, dissolution of sugar in a cup of water. The system is simple because:

- The solubility of sugar in water is very high and unlimited at least with respect to the usual teaspoon of sugar in a cup
- No chemical reaction with another solute or component in water is required to obtain dissolution
- There are no interfering solids, at least yet, assuming we use normal pure sugar.

For sugar in each of the following four forms, rank the required time (0 through 4 with 1 the least time and fastest rate) to completely dissolve one gram of sugar in a cup of water at room temperature:



- powdered sugar
- rock candy
- granular sugar
- cubed granular sugar

This may be obvious to you, but if not, try the experiment. What will be the trend in results if we use boiling water for each of the four sugars? What did we learn from this—or did we already know it? Mineral particle size is important in leaching, with smaller mineral grains leaching faster than coarser mineral grains; and heat usually accelerates the rate of leaching. Now consider two series of experiments, each with powdered sugar, granular sugar and 1 mm rock candy, sized by sieving. In the first series, these 20 g spheres of plaster of paris are formed, each contain 0.20 g (1/5) of one of the sugars uniformly mixed with dry plaster prior to adding a little water and forming the sphere.

The second series of experiments are made by forming three identically sized spheres using coarse sand with a very small amount of glue in a volatile solvent as a binder, just enough to hold the sand grains together.

After the spheres have dried and hardened overnight, obtain six large cups or beakers, place one of the spheres in each and fill it with water. The question is which spheres will permit faster sugar extraction? A easy test of each sugar at intervals of time will allow you to rank each of the six spheres with respect to the rate of sugar extraction using only the following allowed answers: too slow to taste, slow, slowest, fast, faster, fastest.

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plaster of paris with powdered sugar
plaster of paris with granular sugar
plaster of paris with rock candy
sand sphere with powdered sugar
sand sphere with granular sugar
sand sphere with rock candy

Hint: the micro porosity of the sphere composed of cemented sand grains is higher than the micro porosity of the plaster of paris.

As shown in Fig. 1.1, fractional extraction increases with leaching time but the rate of extraction declines as the solute has farther to travel to escape the plaster or sand spheres (and the rock matrix in one leaching), and the concentration gradient, driving diffusion, decreases.

The fractional extraction rate is expected to decrease as the sphere size increases.

Next, imagine the experiment sketched in Fig. 1.2. Actually this is a comparison of the results from two similar experiments but with a distinctive difference. Identical spheres of powdered sugar mixed into coarse sand are used in each experiment. In both experiments the spheres are mounted on a pedestal inside a vertical glass tube. In the first experiment the tube is flooded with water that flows past the sphere at a velocity of 0.1 mm/s (all at a superficial velocity for the process engineers). In the second experiment water flows from an orifice immediately above the sphere onto the top of the sphere and then runs off, simulating a percolation leaching onto the top of the sphere and then runs off, simulating a percolation leaching experiment. The volumetric water flow rates are identical in each case. Which experiment, if either, will yield the faster sugar extraction? The correct answer is: because water wells both spheres there will be little or no difference. Percolation leaching may be a little faster for sufficiently small spheres because of the higher liquid film velocity adjacent to the sphere's surface.

Next, repeat the prior experiment comparing flooded leaching and percolation leaching except thoroughly inundate the surface of each sand

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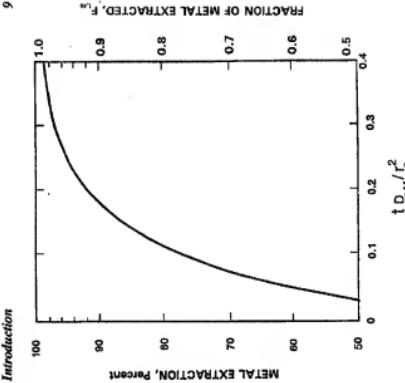


Figure 1.1. Fractional extraction of completely dissolved solute from a porous sphere (Clark, 1936).

sphere with hair spray before beginning the comparative leaching experiments. That's right, common hair spray. According to the can in my wife's bathroom, hair spray contains organic solvents, methacrylates, sebacic acid, hydrolyzed animal protein and other polymers—in other words, greasy stuff. If you use enough hair spray it should prevent any leaching of the sugar.

What are the factors that determine the rates of sugar extraction in these various cases? Consideration of these experiments suggests the following:

- (1) The sugar (mineral) must be soluble in the water (solution).
- (2) The rate of dissolution may depend on the sugar (mineral) grain size.

(3) Sugar (mineral) cannot be extracted from a sphere (rock), such as plaster of paris, that has no open microporosity to permit entry of water (solution) into the sphere (rock) and access to the sugar (mineral) grain.

(4) Sugar (mineral) cannot be extracted if the water (solution) does not wet the rock and enter the micropores by capillary action; this is a function of surface energy and viscosity; hair spray coated the sphere with material that prevents water from wetting and entering the capillaries.

Other factors affecting extraction but not discovered in the proceeding experiments are: (5) sphere (rock) size, (6) ability of solutions to flow by the sphere (rock), sweep away dissolved sugar, and avoid saturation at the sphere (rock) surface, and (7) the total amount of sugar (mineral) in the sphere (rock).

Consider the simplistical case of a small amount of sugar disseminated uniformly within a porous sphere of cemented sand grains. As water enters the pore space, the amount of sugar present is so limited that all is quickly dissolved. Post examination of the saturated wet sphere would show no evidence of sugar grains. How does the dissolved sugar, contained in

water-filled micropores within the sphere, exit the sphere? It occurs by ordinary chemical diffusion and by flow. The solution inside the rock is stagnant. Diffusion is driven by a sugar solution concentration that is higher inside the sphere (rock) than at its surface. How only becomes an important transport process once the dissolved material is out of the sphere (rock); then, soluble sugar is swept away by the solution flowing around the sphere (rock). In the case of percolation leaching this is a slowly flowing film on the surface of the sphere (rock).

MODELING EXTRACTION RATES CONTROLLED BY CHEMICAL DIFFUSION

For most mineral leaching systems, fragmented rocks are roughly equidimensional and can be adequately approximated as spheres. Obviously this would not apply to asbestos or other asbestos mineral morphologies, but these are rarely encountered in commercial solution mining systems.



The spherical approximation simplifies a mathematical description of transport processes within the rock, using one-dimensional polar coordinates. Fracture patterns in an ore body useful for in situ leaching often do not have a preferred orientation and can be similarly approximated. However, the one mass will have a wide distribution of rock sizes from giant boulders (in the case of run-of-mine ore and mine subidence) to very fine particles. Crushing prefer to keep leaching eliminates the boulders and leaves a smaller maximum size, typically about 20 mm, but the rock size distribution will remain wide, with the fractional mineral extraction from the small particles occurring much more rapidly. This situation is usually modeled by dividing the ore mass into a histogram of several (often a dozen) discrete rock sizes, with each size described and simulated by a separate numerical subroutine.

Conventional metallurgical and mineral extraction processes are normally conducted using ground ore to accelerate reactions within process vessels of limited size, with reaction times measured in seconds or minutes, and occasionally a few hours. Solution mining processes usually occur over much longer periods. Rather than a few tonnes of material in the

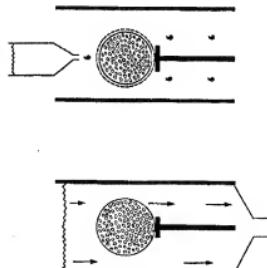


Figure 1.2. Sugar extraction from porous spheres by flooding (left) and percolation (right) leaching.

reactor, many thousands and even millions of tonnes are typically involved. With solution mining, the mineral dissolution process (commonly a homogeneous chemical reaction between the solution and mineral grain) and the internal rock zone diffusion process are usually slower than transport processes outside individual rocks. Therefore, these two slow-step processes tend to govern the overall rate of extraction.

Consider our final sugar example: a simplified case of a small amount of powdered sugar disseminated in a porous sand sphere that is submerged in water. As water enters the micropores of the sand sphere, the small amount of very fine sugar quickly dissolves. Because a limited amount of sugar was all that dissolves without exceeding the solubility limit of the water contained within the rock micropores (pore water); this is our definition of "small amount." Under these restrictive circumstances, the extraction rate is dependent only on diffusion of the sugar solute through the tortuous pore paths within the sphere.

Thus, the leaching extraction model consists of the diffusion equation for a porous sphere with c the local concentration of solute in the pore fluid:

$$\frac{\partial c}{\partial t} = D_{\text{eff}} \left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r} \frac{\partial c}{\partial r} \right). \quad (1.1)$$

The diffusivity D will be that for the sugar solute in water. Since diffusivities for dissolved species in water do not vary much, a reasonable approximation at room temperature is $D = 1.75 \times 10^{-10} \text{ m}^2/\text{s}$ ($1.5 \text{ cm}^2/\text{day}$). The diffusivity of the sphere must be modified by the restriction: microporosity, ϵ , of the sphere (internal fractional volume of water filled open micropores), and by a factor, τ , to account for the tortuosity of the micropores and the resulting greater diffusion path length. Thus, an effective diffusivity results where

$$D_{\text{eff}} = \frac{D}{\tau}.$$

The rock interporosity is sometimes referred to in the hydrogeological literature as secondary porosity to distinguish it from the intraporosity between rocks in a clastic sediment, which is referred to as the primary porosity. An ore heap can be characterized as a clastic sediment. In this text, with respect to ore heaps, the word "intraporosity" is restricted to the interporosity of the rocks, while the interporosity is termed the "void space," or, on occasion, the macro porosity.

Comparison with experimental and calculated results for diffusion in porous media usually results in a tortuosity factor of $\tau=2$. Note that one

unit of time used to express the effective diffusivity is days. Solution mining is a slow process measured in weeks, months, and sometimes years. Periods less than a day are usually relevant. With standard values for the diffusivity and tortuosity used throughout this text unless otherwise stated) the effective diffusivity is:

$$D_{\text{eff}} = 8.7 \times 10^{-4} (\epsilon) \quad [\text{mm}^2/\text{s}].$$

$$D_{\text{eff}} = 0.75 \times 10^{-4} (\epsilon) \quad [\text{cm}^2/\text{d}].$$

For initial and boundary conditions of a negligible sugar concentration outside the sphere and a uniform initial concentration of dissolved sugar within micropores of the sphere, the diffusion equation has been solved (Crank, 1956) to yield the following expression:

$$F_{t, \epsilon} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(-\frac{D_{\text{eff}} n^2 \pi^2 t}{r_0^2} \right) \quad (1.2)$$

where $F_{t, \epsilon}$ is the fractional extraction of sugar in time t for a porous sand sphere of radius r_0 . This infinite series can be adequately approximated as a finite series for computer solution, since the terms in the series quickly become negligible as the index, n , increases. Figure 1.1 is a dimensionless plot of the relationships expressed by eqn 1.2.

EXAMPLE PROBLEM

Uniformly sized porous spherical particles containing sugar were leached over a period of one full day, 24 h, and 60% of the sugar was extracted. If the leaching time is increased to 5 days, predict the percent of sugar that will be extracted using Fig. 1.1... and without using eqn 1.2.

ANSWER

(1) Find the value of D_{eff}/r_0^2 at 60% extraction using Fig. 1.1 and a straight edge or ruler.

$$D_{\text{eff}}/r_0^2 = 0.04.$$

(2) If we increase the time by a factor of five, we must increase D_{eff}/r_0^2 by a factor of five, hence:

$$D_{\text{eff}}/r_0^2 = 0.$$

(3) Again using Fig. 1.1 and a straight edge, find the percent extraction:

$$\text{Answer} = 92\%.$$

Note that several parameters needed to solve the problem with eqp 1.2 were not given (rock microporosity and rock radius), yet with Fig. 1.1, you can solve this practical problem. While you don't know the values of microporosity and radius, you can, with the given data coupled with Fig. 1.1, define the value of D_{eff}/r_0^2 . Whenever you have a set of conditions definable by Fig. 1.1, you can change a variable, such as time in this problem, and find the complimentary variable. You can change more than one variable if you know the initial values of these variables. For example, you could change both sphere microporosity and sphere radius to new values and compute its effect.

Continuing with this problem, what is the required time to obtain 60% extraction if the sphere radius is tripled. Answer: Because of the radius squared effect D_{eff}/r^2 will be $1/(3)^2$ -times its former value (i.e., one-ninth). Therefore the time to obtain the same percent extraction must increase from one day to nine days.

The variables, time, percent extraction and sphere size are easy to measure in a laboratory experiment. Microporosity, and therefore D_{eff} , are more difficult, but not impossible. Normally in doing laboratory work it is most useful to scale from one set of conditions to another using Fig. 1.1.

Recognize that the fraction reacted, F_{ex} , is a function of $1/r_0^2$. Hence, doubling the rock radius, r_0 , increases the time to obtain the same fraction extracted by four.

Figure 1.1 is a dimensionless parametric process design curve for a fairly simple leaching system. Dimensionless parametric design curves for more complex leaching systems will be introduced later in this text. If desired, concentration profiles or sugar within the sphere can be computed by solving the diffusion equation for the initial and boundary conditions (Crank, 1946).

$$\frac{c_i - c}{c_i} = 1 + \frac{2c_0}{\pi r} \sum_{n=1}^{\infty} \left(\frac{(-1)^n}{n} \sin \left(\frac{n\pi x}{r_0} \right) \right) \exp \left(- \frac{D_{\text{eff}} n^2 \pi^2 t}{r_0^2} \right) \quad (1.3)$$

Figure 1.3 schematically shows the sugar concentration within the porous sphere under four conditions: (a) before the sugar containing sphere is submerged into the water (no dissolution of sugar), (b) immediately after submersion and water entry into the micropores causing "instantaneous" dissolution ($t = t_0$), (c) a later time interval t^* , and (d) a still later time interval $t^+ = t_0 + \Delta t$.

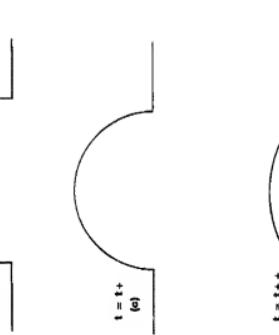
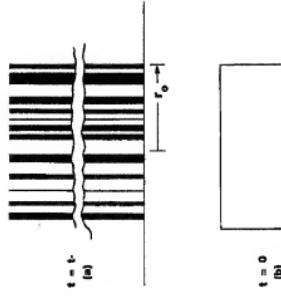


Figure 1.3. Concentration profiles (schematic) across a porous sphere at four time intervals, before and during extraction of a sugar.

PROBLEMS

- Provide your answers to all of the questions posed in this chapter on the dissolution and extraction of sugar contained in spherical solid bodies.
- Ninety percent of the solute is extracted from a spherical sphere in 10 days. How many days are required to obtain only 75% extraction? What is the time to extract 75% from a sphere of the same size with a 25% greater microporosity? Hint: Use Fig. 1.1 directly rather than cumbersome eqn 1.2.
- Estimate the 10^{-1} internal sphere microporosity in the preceding problem, with 10 days to extract 90%, if the sphere diameter is one inch (2.54 cm).
- Estimate the time to obtain 98% extraction of sugar for a sphere with the same microporosity if its diameter is increased to four inches (10.16 cm).

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TWO

Heap Leaching Gold (Silver) Ore —Theory

Enough of sugar; does an important mineral leaching extraction system correspond to the simple example of the previous chapter? Yes, and it's a more exciting commodity—GOLD.

DISSEMINATED GOLD ORE DEPOSITS

Disseminated gold deposits, sometimes referred to as Carlin-type deposits, are the basis for most of the gold mining industry in the United States. When oxidized by nature, these ore deposits are readily heap leached; the gold is present as fine gold particles, one micron (10^{-6} m) or smaller, that are generally not visible except by scanning electron microscopy. The gold particle concentrations often less than 1 ppm, usually found in sedimentary rocks (low porosity) is usually low and open, and with the exception of some highly silicified rocks, the gold is accessible through micropores and microfractures. However, there are asperoids of acceptable gold grade that cannot be mined and heap leached because of their low open porosity. This is caused by a high degree of sinterification that has occurred after or concurrent with gold deposition and blocky micropores. These ore deposits are usually associated with ancient hot springs.

Much of the disseminated gold is believed to have been originally deposited as blebs occluded within pyrite or arsenopyrite grains and, therefore, not originally accessible to dissolution by cyanide solutions. However, many of the shallow ores are now above the water table and were geochemically oxidized, after initial deposition, to alter the sulfide minerals and render the gold leachable. The unoxidized ores containing sulfides may also contain pyrrhotite, a residue of thermally mature petroleum, or other organic material, indicating deposition under reducing environments. These unoxidized ores are almost invariably refractory to cyanide leaching.

Most of these disseminated sedimentary deposits contain silver, which is sometimes the major economic metal. Heap leaching technology for silver is essentially the same as for gold.

Heap Leaching is not useful for all gold ore deposits. Gold particles are dissolved very slowly and heap leaching does not work well on placer deposits because the gold grains are too large. Sulfides and arsenides occlude the gold particles so thin cyanide cannot reach them. Organic material in ore can also sink to obscuring the gold cyanide complex. Consequently, in these carbonaceous ores, the gold is stabilized but not removed from the ore mass. Gold present as tellurides is less common but very difficult to leach with cyanide solutions. High cyanide losses and solution foaming can occur when significant amounts of copper, arsenic, iron and other cyanides are present.

All ores should be evaluated for cyanide gold extraction and cyanide consumption in both mill or agitated leaching tests. If these tests are successful follow them with column testing to simulate heap leaching behavior before proceeding with a new heap leaching project. Nevertheless, the following theoretical discussion is a useful adjunct to ore testing and leaching process understanding.

GOLD LEACHING CHEMISTRY

Gold particles are oxidized and stabilized in the presence of basic cyanide solutions:



This is an electrochemical oxidation reaction that proceeds only because of the great stability of the gold cyanide complex. Oxygen is required for gold dissolution and supplied by air sparging in the leaching of milled ore.

But, the air present in percolation leached heaps is usually adequate because of the small amount of gold present and the limited need for oxygen. Unlike copper sulfide mineral leaching (discussed in a later chapter), the oxygen dissolved in the initial cyanide solution wasting the ore and penetrating rock micro pores at saturation is usually sufficient to dissolve all of the gold in the rock. Comparisons by Wadsworth (1996) based on only the dissolved oxygen at 7 ppm in the pore solution for a Carlin type ore with a measured internal porosity of 0.059 (3.4 vol/pt) indicate a gold dissolution capacity of about 0.07 opt (2 g/tonne); see Fig. 2.1. Furthermore, residual oxygen in the air within 20 vol lci air void space after solution soaking, is at least two orders of magnitude greater than the amount of oxygen required to dissolve all of the gold typically present in heap leached gold ores.

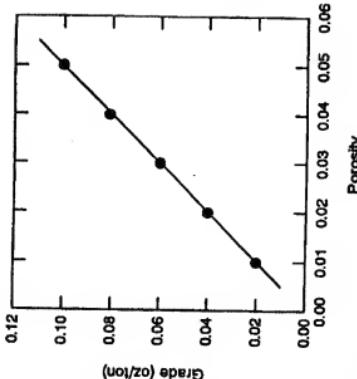


Figure 2.1. Maximum gold grade dissolvable by oxygen in solution saturated micro pores of a gold ore (Wadsworth, 1996).

However, the presence of small amounts of sulfide minerals and organic material can compete with gold for the oxygen in some ores. Consequently, on occasion low residual levels of dissolved oxygen in the pregnant liquor draining from the heap will be encountered, and the lower oxygen concentration in the leach solution will retard the rate of gold extraction from the ore heap. When oxygen must diffuse into the micro pores from outside the ore rocks, there is a small retardation on the gold cyanide complex diffusion out of the rock, which is normally the rate limiting step and described in the next section.

Walsworth (1996) also examined limitations on cyanide diffusion into the solution-filled rock micro pores for a case where the micro pores of a wet ore are initially filled with water without cyanide and later exposed to the cyanide solution when heap leaching begins. Because concentrations of cyanide in the leach solution, typically 50–200 ppm, are much higher than the oxygen saturation limit of 27 ppm, this process is much faster and would account for gold dissolution in hours rather than many days. In a sequence of transport and chemical reaction steps the slowest step will be the 'bottleneck' and is the step that limits the overall rate. Because cyanide diffusion transport is a faster process, due to its much higher concentration, it is not rate limiting.

Further details of gold hydrometallurgy are covered by Baskin (1986)

and Dorr (1950). Practice improvements are covered by Kudryk (1984)

and Desco-Arcos and Miller (1982). The chemistry of silver leaching with cyanide is similar to that of gold:



MODELING DISSEMINATED GOLD ORE HEAP LEACHING EXTRACTIONS

Fortunately, water is the wetting fluid for nearly all rock minerals. During heap leaching, cyanide solutions trickle down over the wetted rocks with solution entering the micro pores by capillary action. Because the gold particles are very fine and sparse, the accessible gold located in open micro pores and fissures of the rocks is quickly dissolved. Once the soluble gold diffuses out of the rock, it is fairly quickly washed from shallow ore heaps that have good permeability. Washing ore heaps will be treated more thoroughly in a later chapter, but for shallow heaps with high uniform permeability this process is mostly completed in a very few days. Thus, fractional extraction, F_t , is reasonably approximated by the diffusion component of

the process, eqn 1.2 (Bartlett, 1974). However, it is worth emphasizing that this is an estimate of the fraction extracted based on only the total extractable metal, which is the free gold accessible to the leaching solution in micro pores of the rocks. Rarely is all of the precious metal contained in ore rocks extractable. Often gold has a higher extractability (getterage) than does silver in the same ore, because, in part, silver more easily forms refractory mineral compounds.

Assuming a negligible concentration outside the rock, because of efficient washing, the estimated soluble gold concentration profiles in a 20 mm diameter rock, calculated from eqn 1.3, are shown in Fig. 2.2 for various times after leaching has started. Calculations for this specific example were based on an assumed rock micro porosity of five percent, $\varepsilon = 0.05$. Concentration profiles will be lower, at the same leaching time interval, for smaller rocks.

The time-dependent fractions extracted for 20 mm through 200 mm diameter rocks, each with five percent micro porosity, are compared in Fig. 2.3, based on eqn 1.2. Rocks larger than 50 mm show insufficient extraction in the time covered by this figure, four weeks. Unsurprisingly, ore from an open pit mine will usually contain a significant fraction of rocks greater than 200 mm, and a plot of fractional extraction versus big time, shown in Fig. 2.4, simply demonstrates that much longer times are needed to complete extraction from the bigger rocks.

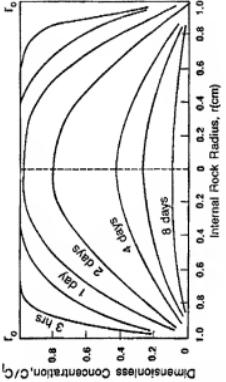


Figure 2.2. Soluble gold concentration profiles in a 20 mm diameter rock with 5% micro porosity at times shown after beginning of heap leaching, eqn 1.3.

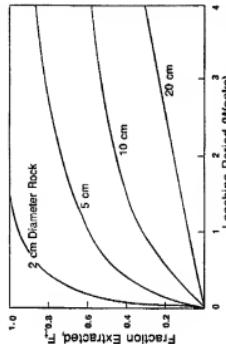


Figure 2.3. Time dependent fraction extracted for heap leaching gold from monzonite rocks with 5% microporosity and the rock diameters shown; eqn 1.2.

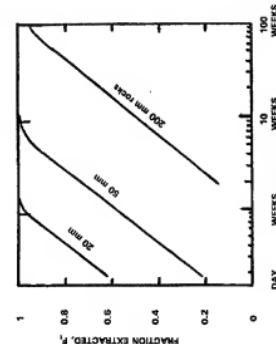


Figure 2.4. Fractional extraction versus \log time for selected rock diameters; eqn 1.2.

Figures 2.2 and 2.3 indicate that for reasonably porous ore crushed to 10–20 mm, most of the gold will be extracted in one or two weeks of heap leaching.

A lowered microporosity can increase the required time for leaching, even when all of the gold is open pore accessible. For most mineral deposits, as the rock microporosity declines increasing amounts of precious metal are locked away and ultimate extractions also decline. Reduced microporosity adversely affects fractional extraction. Results for 20 mm rocks are shown in Fig. 2.5.

Dividing the crushed ore size distribution into a few discrete screen sizes, each weighted by its mass fraction of the total, and with extraction calculations using eqn 1.2, performed on each group yields the time dependent fractional extraction, F_o , for the one heap:

$$F_o = \sum_{j=1}^Y F_{i,j}(N_j) \quad (2.3)$$

$$1 = \sum_{j=1}^Y N_j \quad (2.4)$$

where N_j is the mass fraction of rock group with size i reduced to j .

The fractional extraction as a function of leaching days (time from first appearance of leach solutions draining from the heap) was estimated for

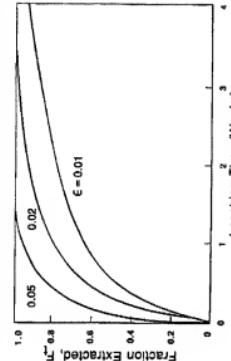


Figure 2.5. Effect of rock microporosity on estimated fractional gold extraction from 20 mm diameter ore rocks; eqn 1.2.

a distribution of rock sizes, using the preceding equations, eqn 1.2, and the largest rock size in each size range. The calculated results for a specific case are shown in Fig. 2.6. Extraction is faster for the size distributed than for 20 mm monosize rocks because of the smaller rocks that are present. This conforms with gold ore heap leaching observations, at least when the heaps are not too high. In practice, a few days to seek the cyanide solution into the ore mass (while simultaneously dissolving most of the gold in place), a week or two for diffusion, and a final few days for washing soluble gold through the low permeability areas of the heap should do nicely for shallow ore heaps. When crushed ore is emplaced, heap leached and removed from a reusable impermeable leaching pad, the duration (forecast by Fig. 2.4), shows good agreement between this simple leaching model and heap leaching practice at gold and silver mines.

Leaching periods of one week to several weeks are usually used with crushed ore, including crushed ore that has been agglomerated. Higher ores (low leachability) require longer periods and, as mentioned, some specially stabilized suspensions cannot be heap leached.

Raw-de-ore, with no rock fragments much greater than 20 mm, will require much longer periods. When heap leaching run-of-mine ore is practiced, the ore is usually permanently stacked, with a series of layers, sometimes referred to as "lifts." Each lift is leached before the next lift is emplaced. Extraction from the larger rocks in buried lifts will continue as the leaching solution trickles down over many months and years.

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ESTIMATING FRACTIONAL EXTRACTION OF DISSOLVED SOLUTE FROM A DISTRIBUTION OF ORE ROCK PARTICLE SIZES USING A DIMENSIONLESS EXTRACTION CURVE

There have been several studies of the particle size distribution resulting from crushing ones and other brittle solids. It has been observed that a logarithmic plot of the cumulative fraction of material finer than a given size versus the corresponding size is usually a straight line with a slope, m , of one, or slightly less. Different, but similar equations have been used to express this relationship, including the well established Gates-Gaudin-Schuhmann (GGS) equation (Schuhmann, 1960):

$$Y(r) = (r/r_c)^m \quad (2.5)$$

with: $0.7 < m \leq 1.0$, where $Y(r)$ is the cumulative fraction finer than size r , and r_c is the radius of the largest rock in the broken ore.

The GGS equation has been coupled with the diffusion equation (eqn 1.1) to develop a numerical relationship for a distribution of particle sizes that is analogous to the dimensionless analytical relationship for monosize particles that was plotted in Fig. 1.1 (Bartucci, 1971). This leads to a relationship in which F_t depends on $D_t a(r^*)^2$. However, a band in the plot of F_t occurs because of the variation in the Gates-Gaudin-Schuhmann breaking function, m , in eqn 2.5, with the boundaries of the band corresponding to the extremes in the breaking function, viz., $m = 1$ and $m = 0.7$. While the value of m can be determined from a log plot of the sieve analysis data, an additional operational problem and error may arise in estimating the

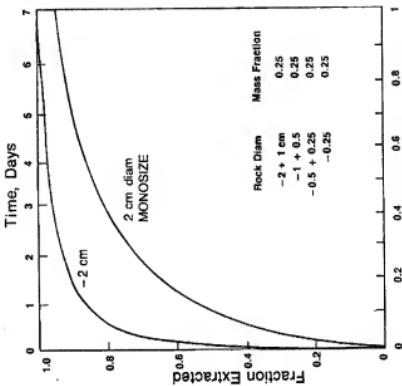


Figure 2.6. Time dependent fractional extraction of gold by heap leaching ore with 5% microporosity and the indicated 20 mm rock size distribution.

largest particle radius, r_s , by extrapolation from a sieve analysis of the ore sample to a particle diameter, d_{so} , for which the undersize mass of particles is equal to 100%—percentage of the total ore sample mass, but less than 100%. Commonly, one sieve analysis is expressed this way using d_{so} , which is the rock diameter at which the undersize particles comprise 80% of the total sample mass. With respect to the Gates-Gaudin-Schuhman distribution, when the breaking function is $m=1$, then from eqn 2.5, $d_{so}/2=0.8r_s$. However, when $m=0.7$ using eqn 2.5, $d_{so}/2=0.72r_s$, which is only about 91% of the d_{so} at $m=1$. This results because there are proportionately more fine particles and the d_{so} shifts to a smaller size as the breaking function shifts from $m=1$ to $m=0.7$, while both are at the same maximum particle size.

Figure 2.7 is a dimensionless plot of the percent extraction of metal, which is $100F$, versus $D_{eff}/(r_s^2)$ when $m=1$. Clearly, at $m=1$, $d_{so}/1.6$ can be substituted for r_s :

$$r_s = d_{so}/1.6. \quad (2.6)$$

Fortunately, and most important, when $d_{so}/1.6$ is defined as r_s at other values of the breaking function within the range $0.7 < m < 1$, and compared with the correct extraction curves computed (Bartlett, 1971) there is a fairly good correlation. It is adequate to the imprecision of sampling ore and characterizing all of the ore, including r_s , from the sieve analysis obtained from the sample.

The definition of eqn 2.6 provides a convenient and practical method of analyzing the extent of metal extraction over time, using the single design curve in Fig. 2.7, with either r_s or d_{so} obtained from an ore sample sieve analysis characterization. Be cautioned that selecting either greater or lower characterizing ore particle diameters than d_{so} leads to distortion from the correct results at $m=1$, which becomes significant as the selected characterizing size variation from d_{so} increases.

Figure 2.7 is a very useful estimating fractional extraction, F_p , as a function of leaching time for any value of d_{so} and $0.7 < m \leq 1.0$, if the effective diffusivity is known. However, an accurate value of the internal incoherence, ε , is needed for D_{eff} and this is difficult to obtain. While internal rock incoherence measurements can be made on small samples, it is difficult to determine if they are representative without making a very large number of expensive measurements. This is essentially a rock internal microscopically sampling problem.

Nevertheless, Fig. 2.7 can still be very useful, because it can first be used to determine an empirical value of D_{eff} for example from the results

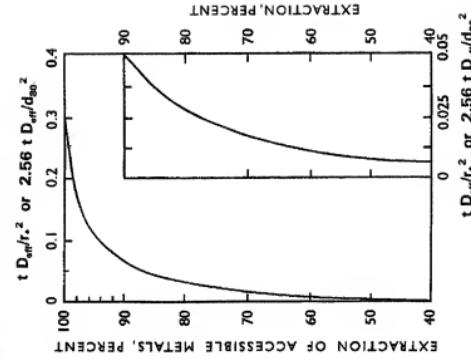


Figure 2.7. Fractional extraction design curve for completely dissolved solution from a uniform aggregation of rocks, as a function of effective diffusivity, D_{eff} , and the d_{so} or r_s , the rock size distribution.

of column one leaching tests. This is done by comparing an experimental fractional extraction obtained at the corresponding leaching time. Ideally, several experiments will be performed to obtain a best value of D_{eff} by averaging the results.

$$D_{eff} = [t \ln(1/F)] / [d_{so}(F)] \quad (2.7)$$

where $Abs(F_i)$ is the abscissa value obtained from the design curve of Fig. 2.7 that corresponds to the fraction extracted, $F_{i,n}$ at leaching time, t_c . After a best value of d_{40} has been determined, t_c can be used to estimate the time required to obtain a desired fractional metal extraction, again using Fig. 2.7. Conversely, for a specified leaching time, the percent of metal extracted can be estimated.

Furthermore, with a reliable value of D determined, a change in the ore size distribution, e.g., from more or less crushing to a new value of d_{40} , can also be accommodated with these relationships to compute its leaching extractions with time.

Caution: The dimensionless group in the abscissa (X-axis) of Fig. 2.7, $d_{40}/(d_{40}/1.6)$, must be in consistent units. For example if D is given in m²/s, then the characterizing rock size, d_{40} must be in meters and the time must be in seconds.

There are two principal problems associated with the use of Fig. 2.7 to determine the leaching rate characteristics of gold and silver ore, or any other ore where transport by diffusion after rapid dissolution of all of the mineral occurs governs the rate of mineral extraction. First, some of the mineral may be locked in plugged micro pores and inaccessible to the leaching solution at the planned crushed size; the gold is not adequately liberated. Second, a finite amount of time is required for the leaching solution to fully penetrate the internal micro pores of the rocks and dissolve the gold, causing an induction period or delay before soluble gold appears in the leachate. While the rate of gold dissolution of micron sized gold particles is relatively fast, hours to several days will be required, depending on the gold particle size. This can extend to much longer times, including weeks and months if nuggets are present. When gold particles larger than a few microns are in the ore they are tantamount to not fully accessible gold within the time of usual heap leaching cycles.

Figure 2.8 displays extraction versus leaching time for a large gold ore sample crushed to 2.5 cm (1 in.), thoroughly blended and divided into fifteen equal portions each of which was used in a cyanide column leaching experiment. The gold in this hypothetical ore is not visible under a microscope. Five leaching periods were used: 4, 8, 9, 12 and 17 days, with triplicate column experiments run at each period. The range of experimental results at each time period is shown in the graph.

Clearly, these results do not match an overlay of Fig. 2.7. However, if Fig. 2.8 is moved to the right and down, a very good fit results, as is shown in Fig. 2.9. This corrected fit can be explained by the following assumptions: First a two day induction period is required for lixiviant

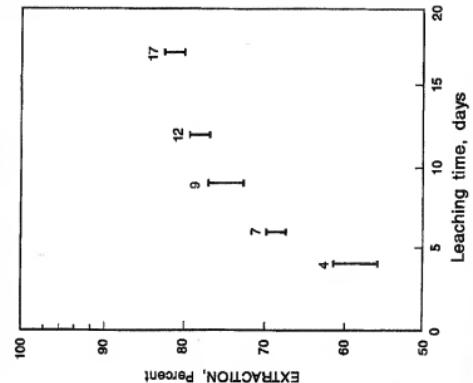


Figure 2.8. Fractional extraction of gold from triplicate cyanide columns are leaching experiments carried out for five time periods.

penetration into the ore and gold particle dissolution, which is reasonable, and second, apparently only about 85% of the gold contained in the ore is accessible to the lixiviant after crushing to 2.5 cm. The remaining gold is presumably locked in micro pores and fissures that are sealed. With this corrected fit, it is possible to make an estimate of the average internal micro porosity in the ore and its effective diffusivity.

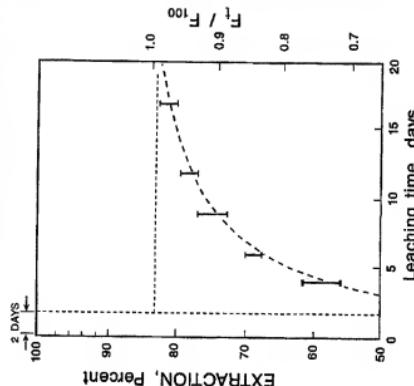


Figure 2.9. Matching the data from Fig. 2.8 to the design curve of Fig. 2.7, using a two-day induction period and limiting the accessible material to 85% of the total material present in the ore.

These data also suggest a further investigation toward improving leaching performance for this ore. For example, will crushing finer than -2.5 cm raise the ultimate possible extraction above 82.8?

VALUABLE MINERAL ACCESSIBILITY TO THE LIXIVIANT AND EXTRACTION

The importance of valuable mineral accessibility to the leach solution cannot be overemphasized. The accessibility, or availability, of the mineral

Table 2.1. Silver Extraction by Column Leaching at Various Crush Sizes for a Bolivian Silver Ore Stockpile.

One Size	Extraction
$-75\text{ }\mu\text{m}$	15.5%
$-25\text{ }\mu\text{m}$	45.5%
-6 mm	64.5%
-2.36 mm (8 Mesh)	65.5%
$-600\text{ }\mu\text{m}$	84.5%
$-150\text{ }\mu\text{m}$	87%

being extracted from the rock to the leaching solution is similar to the concept of liberation of minerals prior to separation (concentration) in mineral processing operations such as flotation. Mineral accessibility often increases as rock sizes decrease. An extreme example of this is shown in Table 2.1, which is a summary of column leaching experiments on a Bolivian silver ore stockpile after crushing to various top sizes. These test results dictated grinding the ore to $600\text{ }\mu\text{m}$ (25 mesh) followed by ore agglomeration before heap leaching. Even then, the leach stage leaching rate was very slow and a long leach cycle of 120 days was selected for this heap leaching operation.

Other characteristics that often affect valuable mineral accessibility include ore grade, host rock, and the other minerals present in the ore mass.

ROCK PARTICLE LEACHING SIZE VERSUS SIEVE PASSING SIZE

In laboratory ore testing practice, aggregates of monosize particles don't exist. The closest approximation is an aggregate of particles passing one size but not passing the next smaller size sieve. The particles will vary in size between the two sieve aperture sizes and it is possible to choose the mean of these to represent the "monosize" particle segregation. However, leaching transport rates depend on the rock radius squared. Hence for purposes of solution mining it is advisable to use an average of the apertures squared for the squared average aperture.

$$d_{\text{ave},\text{ap}}^2 = \frac{1}{2} (d_{\text{ave},\text{lo}}^2 + d_{\text{ave},\text{hi}}^2) \quad (2.8)$$

For the standard sieve sizes, where the next larger sieve aperture is $2^{1/2}$ greater, this leads to

$$d_{45\%} = 0.866 d_{40\%} \quad (2.9)$$

which is slightly larger than the simple mean of the two separating sieve apertures. Computed results of these values are tabulated, with standard sieve sizes, in Appendix Table A-2. This approach can also be used for crushed rock that has been passed through a screen or screener. The use of d_{40} in conjunction with the dimensionless design curves of Fig. 2.7 is preferred because it automatically accounts for variations in the rock-breaking function. However, it is often difficult to determine a d_{40} for coarse crushed ore and two-in-one ore. When d_{40} is not available, but the ore has passed a grizzly or screen so that d_{40} can be computed from the screen size, using Eqn 2.9, then the following relation is recommended as the best available estimate for use with Fig. 2.7:

$$d_{40} = 0.86 d_{45\%} \quad (2.10)$$

and

$$d_{40} = 0.697 d_{49\%} \quad (2.11)$$

Furthermore, if an estimate of r_s is needed, it can be obtained from Eqs 2.6 and 2.11 yielding,

$$r_s = 0.433 d_{49\%} \quad (2.12)$$

EXAMPLE PROBLEM I

Leaching tests of a gold ore crushed to -10 mesh showed that the maximum extraction over an extended period was 90%. Multistage column tests of the ore crushed and screened to pass $-1/16$ in yielded an average extraction of 63% in 7 days. Using Fig. 2.7, estimate the leaching time required for this crushed and screened ore to obtain 85% extraction?

ANSWER

(1) Because only 90% of the gold is extractable (10% is locked), the extraction of accessible gold in 7 days is:

$$63\% \times 0.9 = 70\%$$

and at 85% total extraction the extraction of accessible gold is:

$$85\% \times 0.9 = 79.5\%$$

(2) Using Fig. 2.7, the value of $(D_{\text{eff}}/1.6 d_{40})^2$ at 70% extraction is 0.016.

(3) Using Fig. 2.7 the value of $(D_{\text{eff}}/1.6 d_{40})^2$ at 94.5% extraction is 0.125.

(4) Because the values of D_{eff} and d_{40} have not changed, the leaching time must increase from 7 days, and do so in proportion to the increase in the value of $(D_{\text{eff}}/1.6 d_{40})^2$; hence:

$$t = 7 \text{ days} \times (0.125/0.016) = 54.7 \text{ days.}$$

EXAMPLE PROBLEM II

For the given data of the preceding problem, estimate the value of the effective diffusivity and microporosity of this ore.

ANSWER

(1) First, we must determine r_s , and since we don't know d_{40} , we will estimate r_s from Eqn 2.12:

$$r_s = \frac{1}{2} d_{49\%} = 0.433 d_{49\%} = 0.433(1/12 \text{ in}) = 0.65 \text{ in}$$

$$r_s = 16.5 \text{ mm} = 1.65 \text{ cm.}$$

$$r_s^2 = 2.72 \text{ cm}^2$$

(2) For the given data ($r_s = 7$ and $F_r = 0.70$) and this value of r_s ,

$$r_s^2/F_r^2 = 2.72/7 \text{ cm}^2/d = 0.389 \text{ cm}^2/d$$

and from the previous problem, $D_{\text{eff}}/(r_s^2) = 0.016$ then D_{eff} is:

$$D_{\text{eff}} = (D_{\text{eff}}/r_s^2) \cdot (r_s^2) = 0.016 \times 0.389$$

$$D_{\text{eff}} = 6.2 \times 10^{-3} \text{ cm}^2/\text{d}$$

However, for aqueous solutions,

$$D_{\text{eff}} = 0.75(\epsilon) \text{ cm}^2/\text{d}$$

$$\text{Hence, } \epsilon = 6.2 \times 10^{-3}/0.75$$

$$\epsilon = 0.0083$$

$$\epsilon = 0.63 \text{ percent.}$$

MEASURING INTERNAL ROCK MICROPOROSITY, ϵ

Internal rock microporosity is measured by comparing the mass of a dried rock sample with the same sample first dried and then saturated with an

injected liquid. Drying is conducted at a modest temperature to prevent removal of chemically bound water, e.g., 105°C for 48 hr or more. If total microporosity is supplied then pressure injection of mercury using a mercury porosimeter can be used. Pressure forces the mercury into all of the open micropores regardless of pore size. For purposes of heap leaching it is easier and more valid to soak a previously dried sample in water for an extended period of time, typically at least 48 hr. Micropores not filled by this procedure are generally too small to be involved in the leaching process. The volume of the rock sample, including the internal microporosity, is determined from the volume of water displaced upon submergence of the dried but weighed sample. The water soaked sample is dried and immediately weighed. Its mass is compared with the dry sample mass to obtain the mass and thereby the volume of internal water contained in the sample. Comparing the two volumes yields the fractional volumetric microporosity, ϵ .

PROBLEMS

- Estimate and plot on graph paper Fraction extracted, F_n , versus weeks of leaching time for stabilized gold in a disseminated ore with 0.03 microporosity for each of the following monosize ore fragments:
 - 2 mm diam. rock.
 - 20 mm diam. rock.
 - 80 mm diam. rock.
- On/off heap leaching of crushed ore with a reusable pad at the New Opal Mine is providing an average gold extraction that is 80% of the accessible gold in the ore. Using Fig. 2-7, estimate the extraction of accessible gold that will be obtained if the leaching time is doubled.
- For an ore with a ϕ of 2.0 it is recommended a leaching time to obtain 90% extraction. The internal microporosity is unknown but not expected to be less than 0.005 (0.5%).
- Using the data presented in Figs. 2-8 and 2-9, estimate the average value of the internal rock microporosity in this ore, which was repeatedly crushed and sieved until all of it passed a one inch nominal sieve.
- An on/off gold heap leaching operation using two crushing stages to produce rock that passes through a two inch screen (nominal) obtains 55% extraction of the accessible gold in the ore. (a) Using Fig. 2-7 and Table A-2, predict the percent extraction of accessible gold that will be obtained if a third crushing stage and larger screen decks are installed

Heap Leaching Gold (Silver) Ore—Theory

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be turned off. Drainage will continue to occur for several days after solution application ceases.

Make-up chemical reagents, added to the barren solution being returned to the ore heap, include water to supplement evaporation losses in dry climates, sodium cyanide, and usually caustic (NaOH) to provide protective alkalinity in a pH range between 10 and 11. Caustic is often preferred over less expensive lime in order to reduce calcium carbonate scaling in the pipelines. Small amounts of proprietary scaling inhibitors are also continuously injected into the returning barren solution. Consumption of caustic is often reduced by adding less expensive lime, in a small fixed amount, to each truck while hauling ore to the heap. Dumping onto the heap provides crude, but adequate mixing and the excess calcium is retained in the heap rather than depositing in pipelines.

Metal recovery occurs either by (1) adsorption on hard-shell activated carbon or (2) zinc precipitation, after purging excess dissolved oxygen, using the Merrill-Crowe process. Both zinc precipitates and metal stripped from the activated carbon are smelted to a dead bullion. Because the metal loading capacity of activated carbon is limited, the economic value of silver loaded carbon is quite modest. For this reason, zinc precipitation is usually selected when an economically significant amount of silver is being extracted from the ore.

HEAP CONSTRUCTION

Heaps are constructed by (1) dumping from haul trucks, (2) stacking with a front-end (wheel) loader, and (3) mechanical stacking using conveyor belts. Two truck dumping methods, (1) over end dumping and (2) stacking, or plug dumping, are illustrated in Fig. 3.2.

The major problem with heap construction using haul trucks is the compaction and extreme loss of permeability in the upper few feet of the heap caused by truck wheel pressure. This is less serious with hard ore, but soft ore will crush and produce a virtually impervious top layer. Because dozers and other track vehicles produce very low ground pressure, they are used to level and rip the surface of the heap, as deeply as possible, after construction and prior to leaching. This breaks up the compaction zone and improves permeability.

Front-end loaders travel on the leach pad surface to stack the ore in a heap. Consequently, the loader does not cause compaction on top of the heap. Depending on their size, front-end loaders can construct heaps from 3 to 5.5 m high.